Edge Intrinsic Rotation: Theory and Experiment

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Overview

A simple kinetic transport theory predicts strong linear dependence of edge intrinsic toroidal rotation on $\bar{R}_X \doteq (R_X - R_{\mathrm{mid}})/a$, with R_X the major-radial position of the X-point.

- "Edge" means the radial range of a cm or so both inside and outside the LCFS, where spatial variation is rapid.
- An analytic calculation yields a simple formula v_{pred} for the toroidal rotation at the core-edge boundary.

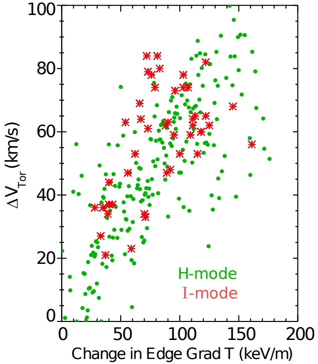
A series of Ohmic L-mode shots on TCV, scanning $\bar{R}_X$, showed:

- Entire rotation profile shifts rather rigidly as $\bar{R}_X$ changes.
- Linear dependence of edge rotation on $\bar{R}_X$ ($\checkmark$)
- Rotation sign change for adequately outboard X-point ($\checkmark$)
- Fits of rotation vs $\bar{R}_X$ give reasonable values for theory's two input parameters ($\checkmark$)

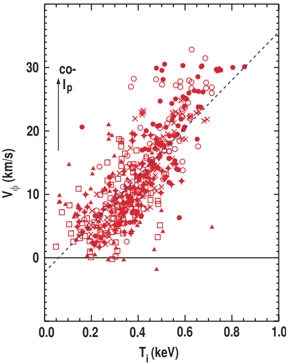
Outline

- Theoretical model
  - Assumptions
  - Ingredients of analytical calculation
  - Cartoon of model
  - Resulting predictions
- Experiment
  - TCV features
  - Rotation profiles for different R_X
  - Qualitative and quantitative comparison with model
  - Consideration of other models

Experimentally, tokamak plasmas rotate spontaneously, without external torque.



Rice et al PRL 2011, Fig. 5b



deGrassie et al NF 2009, Fig. 7

- Co-current in the edge.
- $v_\phi / v_{ti} \sim O(0.1)$ at the core-edge bound.
- Edge rotation proportional to T or ∇T?

- Spin-up at L–H transition.
- Roughly proportional to W/I_p.

Edge orderings relevant for intrinsic rotation

Influence of SOL$\Longrightarrow$nonlocal, steep gradients, strong turbulence, very anisotropic

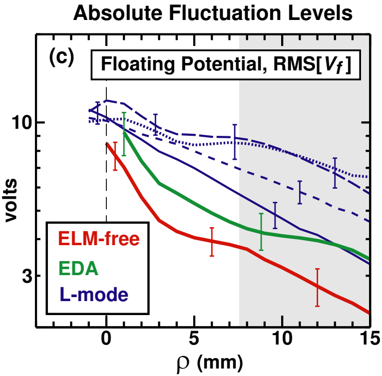
Lengths: $\frac{L_\perp}{a}, \frac{a}{qR} \ll 1$, $k_\parallel \sim \frac{1}{qR}$, $\frac{k_\parallel}{k_\perp} \lesssim k_\parallel L_\perp \lll 1$

Rates: $\frac{D_{\text{tur}}}{L_\perp^2} \sim \frac{v_{ti}|_{\text{sep}}}{qR} \lll \omega \sim \frac{v_{ti}}{L_\perp}$

$D_{\text{tur}} \sim \tilde{v}_{Er}^2 \tau_{\text{ac}} \sim \tilde{v}_{Er}^2 / k_\perp \tilde{v}_{Er} \sim c\tilde{\phi}/B$
decreases in r near LCFS, on scale $L_\phi \sim L_\perp$

$\Delta v_\parallel|_{\text{turb}} : \left(\frac{\Delta v_\parallel|_{\text{turb}}}{v_{ti}}\right)^2 \sim \frac{k_\parallel}{k_\perp}\left(\frac{T_e}{T_i}\frac{e\tilde{\phi}}{T_e}\frac{1}{k_\perp \rho_i|_{\text{sep}}}\right) \ll 1$

Wide passing-ion orbits: $\delta \doteq \frac{q\rho_i}{L_\phi} \sim O(1)$



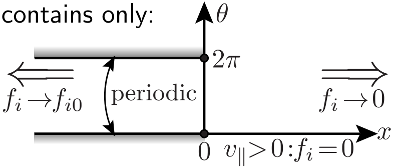
LaBombard et al NF 2005, Fig. 8.

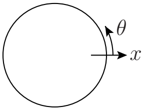
A simple kinetic transport theory models edge intrinsic rotation.

$$\partial_t f_i + v_\parallel \partial_\theta f_i - \delta v_\parallel^2 (\sin\theta)\,\partial_x f_i - \partial_x \left[D(x,\theta)\, \partial_x f_i \right] = 0$$

Extremely simple kinetic transport model contains only:

- Free flow along the magnetic field
- Radially-directed curvature drift
- Radial diffusion due to turbulence
  - Diffusivity stronger outboard, decays in x
- Two-region geometry
  - Confined edge: periodic in θ
  - SOL: pure outflow to divertor legs



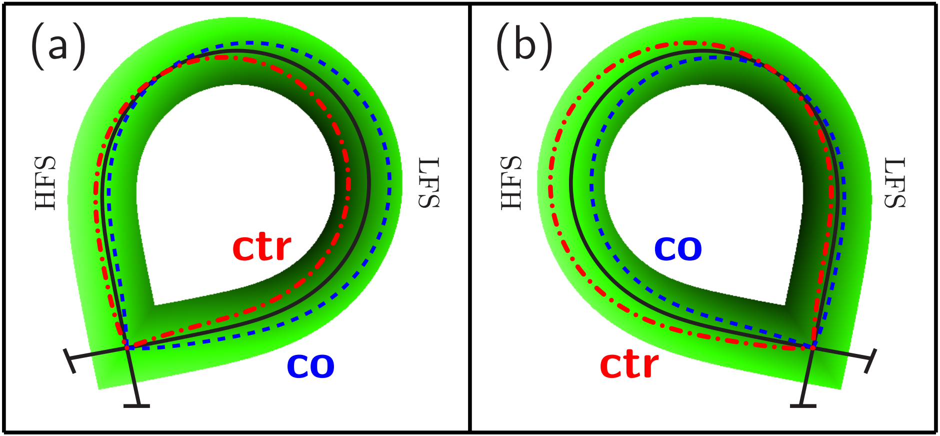


After some variable transforms, obtain steady-state equation

$$\partial_{\bar\theta} f_i = D_{\mathrm{eff}}\left(v_\parallel\right) \partial_{\bar x}\left(e^{-\bar x} \partial_{\bar x} f_i\right),$$

in which D_{eff} depends *on the sign* of $v_\parallel$.

Asymmetric diffusivity caused by drift orbits' interaction with ballooning transport and X-point angle.



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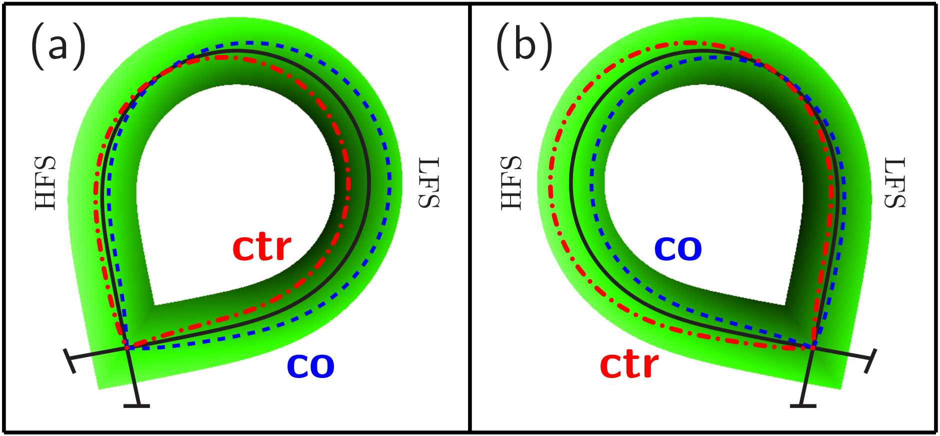
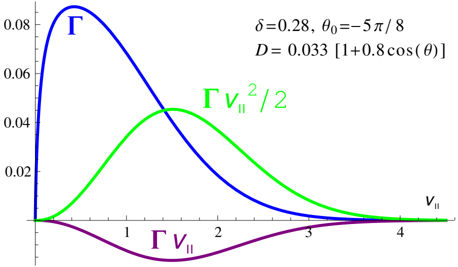


Edge rotation may become counter-current for outboard X-point!

Suprathermal ions drive a robust momentum flux.



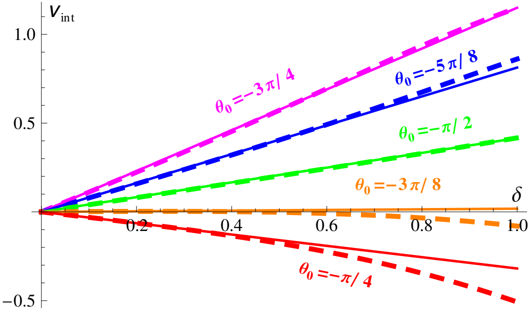
Assume a Maxwellian at the boundary with the core,

$$f_{i0}\left(v_{\|}\right) = (2\pi)^{-1/2}\exp(-v_{\|}^2/2),$$

then moments of the transport are just

$$\Gamma^p \doteq \int_{-\infty}^{\infty} \Gamma\left(v_{\|}\right) dv_{\|},\quad \Pi \doteq \int_{-\infty}^{\infty} v_{\|}\Gamma\left(v_{\|}\right) dv_{\|},\quad Q_{\|} \doteq \frac{1}{2}\int_{-\infty}^{\infty} v_{\|}^2\Gamma\left(v_{\|}\right) dv_{\|}.$$

Vanishing momentum transport: pedestal-top intrinsic rotation.



$$0 = \int_{-\infty}^{\infty} \left(v_{\text{int}} + v_{\parallel}\right) \Gamma\left(v_{\parallel}\right) dv_{\parallel} = v_{\text{int}} \Gamma^p + \Pi$$

$$\boxed{v_{\text{pred}} = -\frac{\Pi}{\Gamma^p} v_{ti} \approx 0.104 \left(\frac{1}{2} d_c - \bar{R}_X\right) \frac{q T_i(\text{eV})}{L_\phi(\text{cm}) B_0(\text{T})} \text{km/s}}$$

- $D = D_0(1 + d_c \cos\theta)$
- $1/B_\theta \Rightarrow 1/I_p$
- X-point angle dependence
- Co-current for typical parameters
- Rotation magnitude $O(v_{ti}/10)$
- L-H spin-up due to $\Uparrow T_i$, $\Downarrow L_\phi$

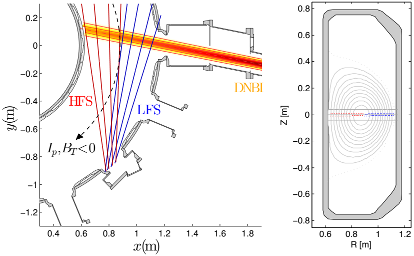
TCV is well-suited to investigate R_X-dependent edge rotation.

Extreme geometric flexibility:

- Vary R_X from inner to outer wall
- Both LSN and USN

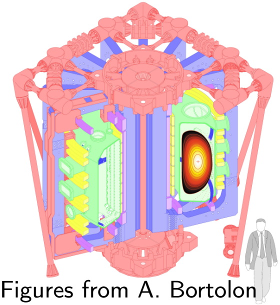
Diagnostic NBI for CXRS on C^{6+}:

- applies negligible torque ($\sim 1\% \tau_{\mathrm{int}}$)
- LFS & HFS viewing chords



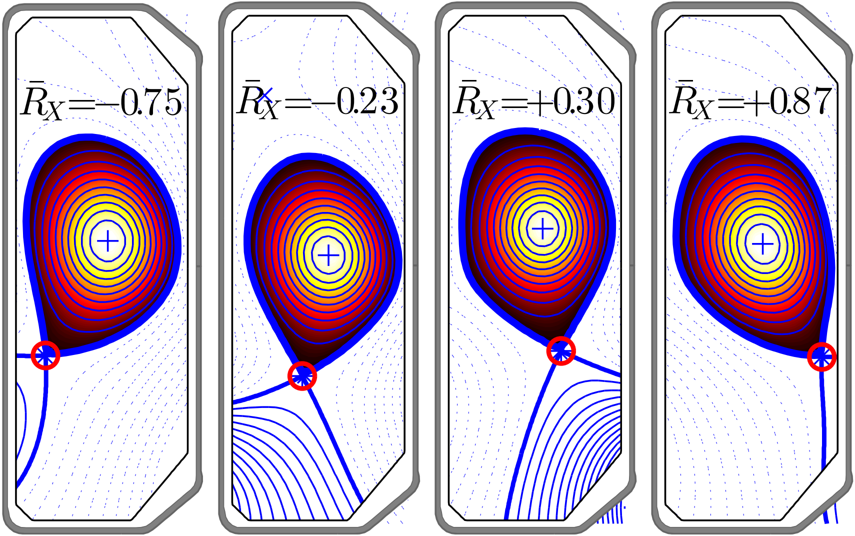
Parameter ranges for this experiment:

X-point major radius (R_X)	0.675–1.085m
Major radius (R_0)	0.88–0.89m
Minor radius (a)	0.22–0.23m
Edge safety factor (q_{eng})	3.6–4
Plasma current (I_p)	150–155kA
Electron density ($n_{e,\mathrm{avg}}$)	1.4–$2.2\times10^{19}\mathrm{m}^{-3}$
Elongation (κ)	1.35–1.45
Triangularity	-0.3 – +0.4



Figures from A. Bortolon

Discharges with R_X from inner to outer wall, LSN and USN.



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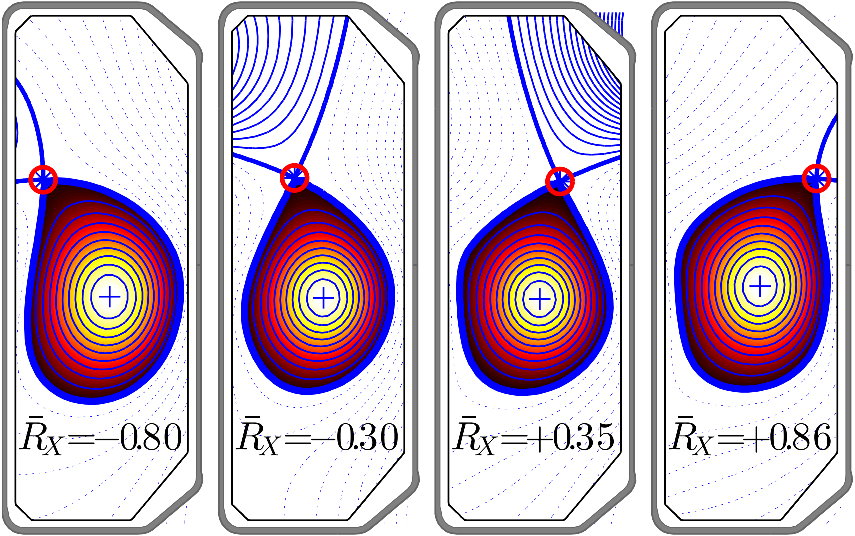
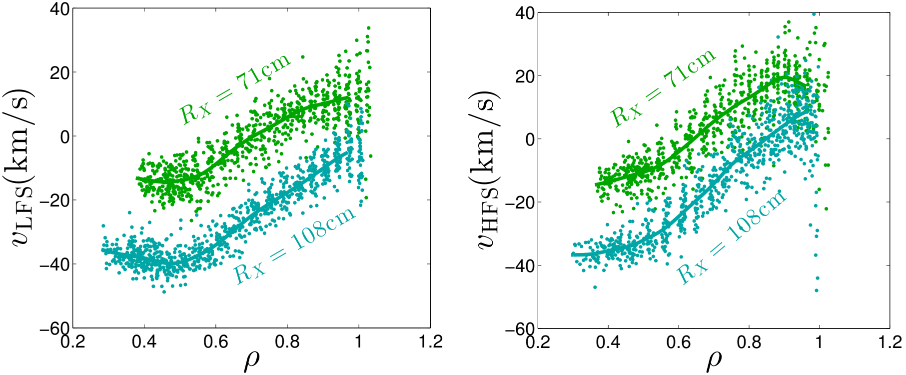


Changing $\bar{R}_X$ indeed shifts the boundary rotation, shifting the whole rotation profile with it.



Measured carbon rotation profiles for an inboard ($R_X = 71\mathrm{cm}$) and outboard ($R_X = 108\mathrm{cm}$) X-point.

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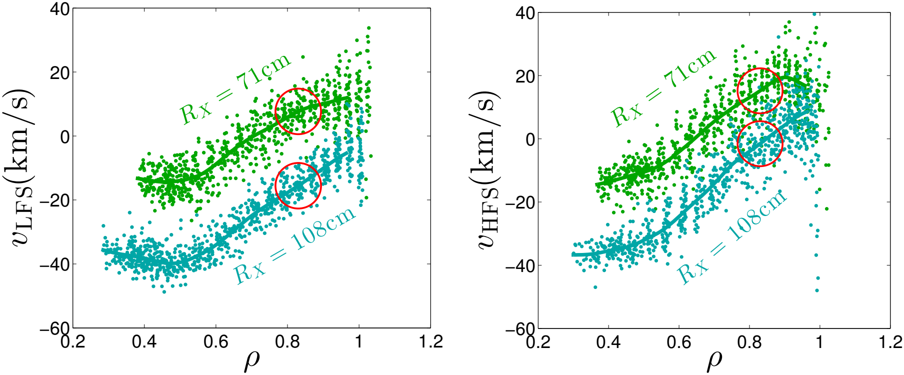


Measured carbon rotation profiles for an inboard ($R_X = 71$cm) and outboard ($R_X = 108$cm) X-point.

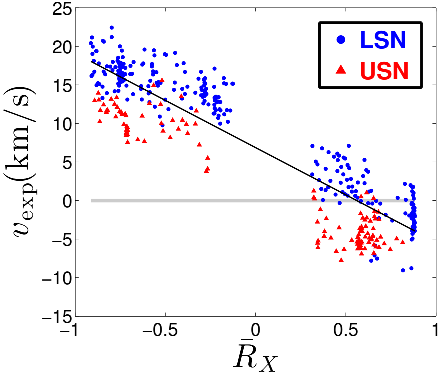
Theory-Experiment agreement is surprisingly good.

Roughly linear dep of v_{exp} on $\bar{R}_X$.

- Counter-current for large $\bar{R}_X$.

Reasonable fitting parameters:

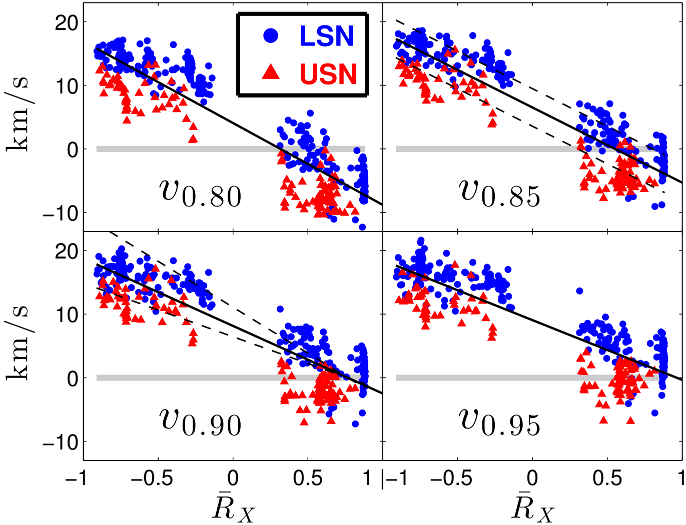
- $d_c \approx 1.1$: outboard ballooning
- $L_\phi \approx 4.1\mathrm{cm} \approx 1.5 L_{Te}$
  - L_ϕ ≈3.8cm from LP meas
  - $L_\phi \approx$ 1–2L_{Te} on other expts



USN$\sim$ 6km/s more counter-current than LSN.

Some mid-range R_X inaccessible due to machine constraints

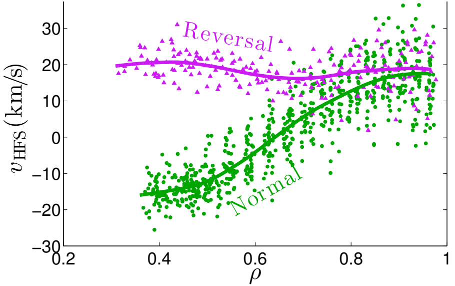
The basic trend holds for alternate radial positions.



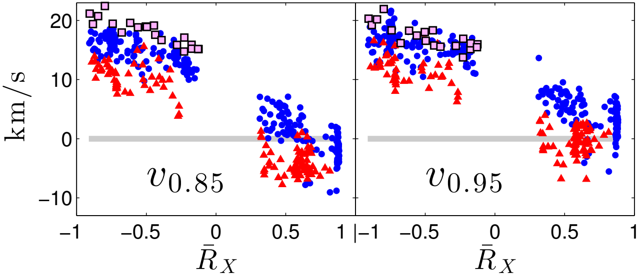
Core rotation reversal seems to have little effect on edge rotation.

Spontaneous core rotation reversal well-known on TCV (Bortolon et al PRL 2006)

Accidentally triggered reversal in shots 48152–48153, due to larger I_p

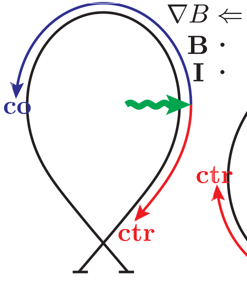


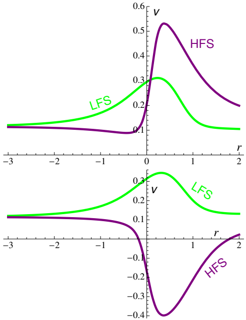
Theory: in the absence of actual core torque, rotation peaking does not affect edge momentum flux, thus intrinsic rotation is maintained.



Can transport-driven SOL flows drive rotation in the confined plasma?

Intrinsic rotation velocity is determined by vanishing momentum flux.
Although transport-driven toroidally-asymmetric flows exist in the theoretical calculation, they do not drive rotation at the boundary with the core plasma.

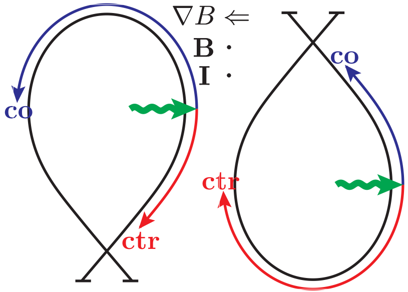


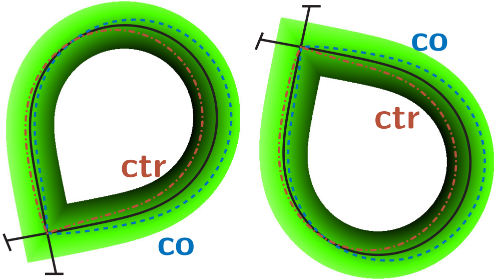


$$v_\parallel \partial_\theta f_i - \cancel{\delta v_\parallel^2 (\sin\theta)\, \partial_x f_i} - \partial_x \left[D(x,\theta)\, \partial_x f_i \right] = 0$$

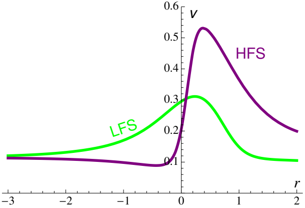
Favorable/unfavorable ∇B comparison can clarify physics.

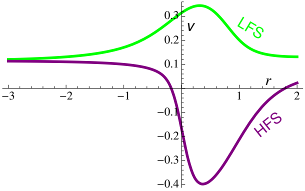
Reverses transport-driven flows but not orbit shifts and their flows.





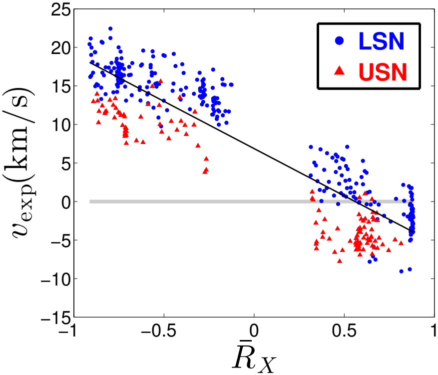
LSN:





:USN

Rotation data consistent with dominant drive by orbit shifts.

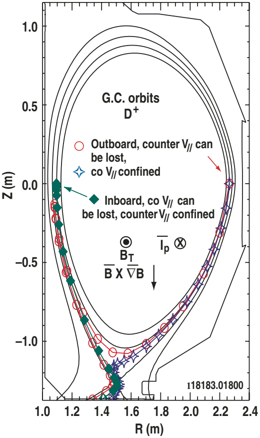


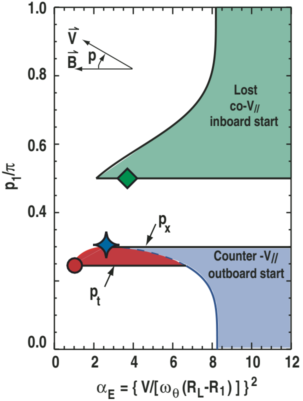
Dominant variation of rotation unaffected by LSN→USN.

However, reason for LSN-USN rotation difference remains unexplained, maybe geometry interacts with: collisional effects, trapped particles, particle sources/sinks

Or maybe LSN vs USN just affects turbulence properties like d_c or L_ϕ

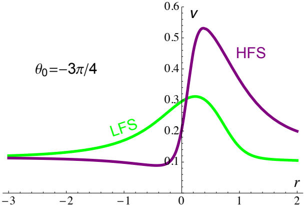
Do orbit losses explain rotation at the core-edge boundary?





deGrassie et al NF 2009, Figs. 8–9

Ion orbit losses are one way of looking at the origin of the edge flow layer. However, the effect of the edge flow layer is determined by momentum transport physics.



$$v_\parallel \partial_\theta f_i - \delta v_\parallel^2 (\sin\theta)\, \partial_x f_i - \cancel{\partial_x [D(x,\theta)\, \partial_x f_i]} = 0$$

Summary

- Simple theory for intrinsic rotation due to interaction of:
  - spatial variation of turbulence
  - different radial orbit excursions for co- and counter-current passing ions
- Predicted rotation depends strongly on $\bar{R}_X$
- Performed series of Ohmic L-mode shots on TCV, scanning $\bar{R}_X$
  - Change of $\bar{R}_X$ shifts entire rotation profile, fairly rigidly
- Experiment and theory appear fairly consistent
  - v_{exp} depends about linearly on $\bar{R}_X$, goes counter-current for large $\bar{R}_X$.
  - Linear fit results in reasonable adjustable parameters d_c, L_ϕ.
  - Basic results hold for various alternate radial positions.
  - v_{exp} appears fairly insensitive to core rotation reversal.
- Possible further topics:
  - $\mathbf{E} \times \mathbf{B}$ drift, collisions, real magnetic geometry and orbits/trapping
  - Self-consistent calculation of turbulence properties: d_c, L_ϕ, ...
  - Why is USN rotation more counter-current than LSN?